



Effect of angled abutments in the posterior maxillary region on tilted implants: a 3D finite element analysis

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Abstract

The aim of this study was to evaluate the bone tissue effects under dynamic loading using finite element analysis (FEA) for four angled abutments with different deviated palatal lateral tilt angles. A three-dimensional model of the posterior maxillary region and an implant crown model were reconstructed and assembled with a three-dimensional model of the implant, angled abutment, and central screw to create a total of 10 three-dimensional finite element models tilted at 15°, 20°, 25°, and 30° in three groups, and the dynamic loads simulating oral mastication were loaded on the implant crown to analyze the equivalent stresses and strains in the peri-implant bone tissues. Under the dynamic loading, the cortical bone on the buccal side of the implant neck showed different degrees of stress concentration, and the cortical bone stress was much higher than the cancellous bone, and the strain concentration area of each model was located in the bone tissue around the implant neck and base. For the use of angular abutment, under the premise that the cortical bone stresses and strains of the 10 models meet the requirements for use, the peak stresses of 2.907 MPa, 3.018 MPa, and 2.164 MPa were achieved by using the 20° angular abutment to achieve the tilt angles of 20°, 25°, and 30° implantation, which is more advantageous compared with other models.

Keywords Angle abutments · Tilted planting · Biomechanics · Finite element analysis

Highlights

- The effect of angled abutments and tilted implant angles on the biomechanical aspects of peri-implant bone was investigated.
- A theoretical guide to the clinical application of angled abutments for tilted implants in the maxillary posterior region.
- The bone tissue effects of four angled abutment tilt implants with different off-palatal tilt angles under dynamic loading were investigated.

- In the case of tilted first molar implants in the maxillary posterior region, the area of strain concentration is located in the bone tissue around the neck and base of the implant.

1 Introduction

Tooth loss can adversely affect the masticatory ability and facial aesthetics of the patient's mouth, which can damage their self-confidence and increase their psychological burden. Clinically, the vertical bone height in the maxillary posterior region is severely insufficient, and dental defects occurring in the maxillary posterior region account for 30% of the total number of dental defects [1]. The remaining bone height of the first maxillary molar region was less than 5 mm in 73.1% of cases [2], which is mainly related to the maxillary sinus pneumatization, severe resorption, and atrophy of the alveolar bone, etc., and will limit implant restorations in the maxillary posterior region. Currently, dental implants have become the main clinical treatment for tooth loss, while the success of implantation is closely related to the bone

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volume and quality of the patient's alveolar bone [3]. The natural structure of the maxillary posterior region, combined with localized alveolar bone resorption due to long-term tooth loss, makes this region highly susceptible to bone deficiency, which significantly increases the challenge of implant treatment [4]. Previously, maxillary sinus elevation, bone grafting, or guided bone regeneration were mostly used to treat bone deficiency, but the above treatment techniques are more complicated, more invasive, more intraoperative and postoperative complications, and patients have heavy postoperative reactions.

When faced with the effects of insufficient bone volume in the maxillary posterior region as well as anatomical structure, tilted implants using angled abutments can ameliorate the effects of poor implant position. An angled abutment is one in which the long axis of the abutment is not in a straight line with the long axis of the implant, but at an angle, and the angle between the two is the size of the abutment angle [5]. Angled abutments can be implanted in combination with the patient's existing bone tissue conditions, avoiding the trauma caused by bone grafting or postoperative infection in the bone grafting area, reducing the patient's pain, and shortening the restoration cycle; however, angled abutments with tilted implant structures are different from straight abutments in that they change the occlusal force conduction, which changes the distribution and size of the occlusal force within the peri-implant bone tissues, and has a certain impact on peri-implant bone tissue differentiation and remodeling [6], therefore, the use of angled abutments is somewhat limited in clinical practice.

The technique of tilting implants in the residual crestal bone of patients with maxillary atrophy has been shown to provide several clinical advantages. It allows the placement of longer implants, thus increasing implant-bone contact area and implant primary stability. The technique of using tilted implants allows the implant to be placed along the anterior wall of the maxillary sinus in a proximo-medial tilt, or in a distal-medial tilt at the maxillary tuberosity, or sometimes in a bucco-palatal tilt [7], avoiding the maxillary sinus and making full use of the remaining bone volume. In the maxilla, the palatal tilt of the implant increases the bone density in this region and the increased palatal tilt decreases the labio-buccal bone resorption [8]. In contrast, in the maxillary anterior region, a tilt to the labial side can jeopardize its stability [9].

Since Branemark proposed the theory of osseointegration, with the progress of biomaterials and implant surgery, tilted implant and restoration techniques have been greatly developed and many clinical patients have been treated satisfactorily. A systematic review and meta-analysis have shown that tilted implants do not increase the rate of implant failure and the degree of bone resorption, and have better short-term results [9], with tilted implant retention rates of 95 to

100% [10]. With the development of implant technology, the use of remaining bone volume for tilted implant placement has become an alternative method to address the lack of vertical bone volume in the maxillary posterior region. It has been shown that tilted implant placement significantly reduces the rate of mucosal perforation, avoids complex bone augmentation procedures, and increases the success rate of implants [11]. Del Agliardi E [12] followed 308 vertical implants and 308 inclined implants in 154 patients for 5 years and demonstrated that there was no statistical difference in the degree of bone resorption between vertical and tilted implants.

Biomechanical factors can directly affect the success of implantation [13, 14]. Late implant failures are primarily related to biomechanical complications; thus, the major factor leading to such failures may be a lack of understanding of biomechanical factors [15, 16]. One of the key factors in the success or failure of dental implants is the way in which stresses are transferred to the surrounding bone [17]. The transfer of a load from implants to the surrounding bone depends on the type of loading, the nature of the bone-implant interface, the length and diameter of the implants, Angle abutments, angulation of implants in bone, the shape and characteristics of the implant surface, the prosthesis type, and the quantity and quality of the surrounding bone [18, 19]. Some of these biomechanical factors are inherent with the patients, and others can be controlled by clinicians.

Three-dimensional finite element analysis (FEA) has been widely used for the quantitative assessment of stresses in implants and their surrounding bone [20]. Among different mathematical approaches, FEA is commonly used to assess the influence of clinical factors on implant survival and to predict the biomechanical status associated with the different implant and alveolar bone conditions [21]. FEA can predict the stress distribution in the contact area between the implant and the cortical bone, as well as the stress distribution of the implant tip in the surrounding bone. This approach facilitates the solution of complex structural problems because it divides them into smaller and simpler interrelated parts by using mathematical techniques [22].

There are relatively more studies on the use of angled abutments for tilted implants, but there are fewer studies on how to rationally use angled abutments to plan the tilting angle of the implant to promote good osseointegration between the implant and the surrounding alveolar bone. Therefore, in this study, the three-dimensional finite element model of four types of angled abutments for tilted implantation was established to investigate the changes in the stress distribution of the alveolar bone around the implant when tilting the abutments at 15°, 20°, 25°, and 30° under the simulated dynamic loads of oral mastication, so as to provide theoretical evidence for the rational use of angled abutments in the process of clinical implant restorations.

2 Materials and methods

The detailed method of development of the 3D Finite Element models is mentioned below.

2.1 Geometrical modelling

As shown in Fig. 1, the geometric model includes cortical bone, cancellous bone, sinus cortical bone, maxillary sinus mucosa, implant crown, implant body, angled abutment, and intermediate screw portion.

2.1.1 Generation of bone tissue

The atrophic posterior maxillary model was created from cone-beam computed tomography (CBCT) images, which were obtained from the Department of Oral Radiology, Zhongshan Hospital, Fudan University, for use in the implant planning of the actual patient (the subject had informed and consented to the experiment). Images were acquired using CBCT equipment (Kavo 3D eXam i, Kavo, Germany) at 120 KV and 5 mA using a 9-inch field of view with an axial slice thickness of 0.2 mm and isotropic voxels. The CBCT medical image data were saved in DICOM format and STL data of the posterior maxillary region were acquired using Mimics research 21.0 (Materialize, Belgium), imported into Geomagic Studio 2021 (Geomagic, USA) software, and processed to obtain cortical bone, cancellous bone, sinus cortical bone, and maxillary sinus mucosa in Step format. The posterior maxillary alveolar bone is classified as type IV bone and described as cortical bone surrounding dense cancellous bone [23].

2.1.2 Generation and placement of the implant portion

Implants, angled abutments, intermediate screws modelled with reference to the parameters of the Bego RS/RSX series implants, abutments and restorative screws, implants 4.1 mm × 10 mm; As shown in Fig. 2, the angular abutments are designed as 15°, 20°, 25°, and 30°, recorded as A, B, C, and D, respectively; the central screw is 1.8 mm × 9.3 mm. Based on the parameters of the implant, abutment, and central screw models, a solid model was built using SolidWorks 2021 (Dassault, France) software.

The cortical bone, cancellous bone, sinus cortical bone, maxillary sinus mucosa, implant bone, implant, abutment, central screw, and crown restoration are imported into SolidWorks 2021 software for combined assembly. According to the variation of angle abutments, as shown in Fig. 3, a total of 10 models were established in 3 groups. Among them, A_{15° and B_{20° in Group I and A_{15° in Group II and B_{20° in Group III are the same models. In order to facilitate the comparison and analyze the connection between the angular abutment and the tilt angle, each of the 10 models was recorded as: which were recorded as: I: A_{15° , B_{20° , C_{25° , and D_{30° ; II: A_{15° , A_{20° , A_{25° , and A_{30° ; III: B_{15° , B_{20° , B_{25° , and B_{30° . Where, the capital letter is the abutment used by the model, and the lower right degree is the degree of inclined planting on the off-palate side of the model.

2.2 3D finite element modeling

As shown in Fig. 1, the parts of the model of the maxillary posterior region that were not relevant to the calculation were excised and cut in SolidWorks software using the outer contour tangents of the proximal and distal centers of the

Fig. 1 Geometric model. The geometric model consists of cortical bone, cancellous bone, sinus cortical bone, maxillary sinus mucosa, implant, abutment screw, and angled abutment

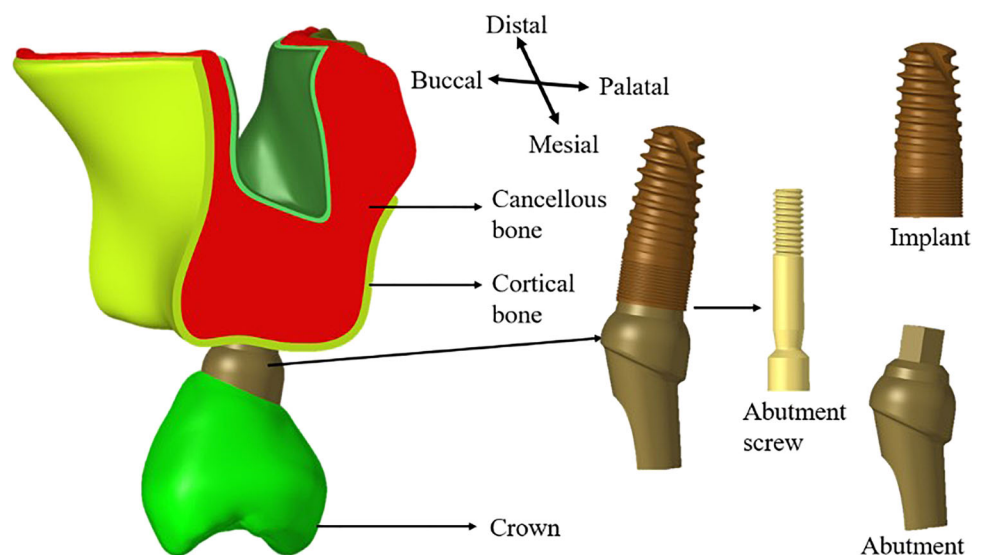
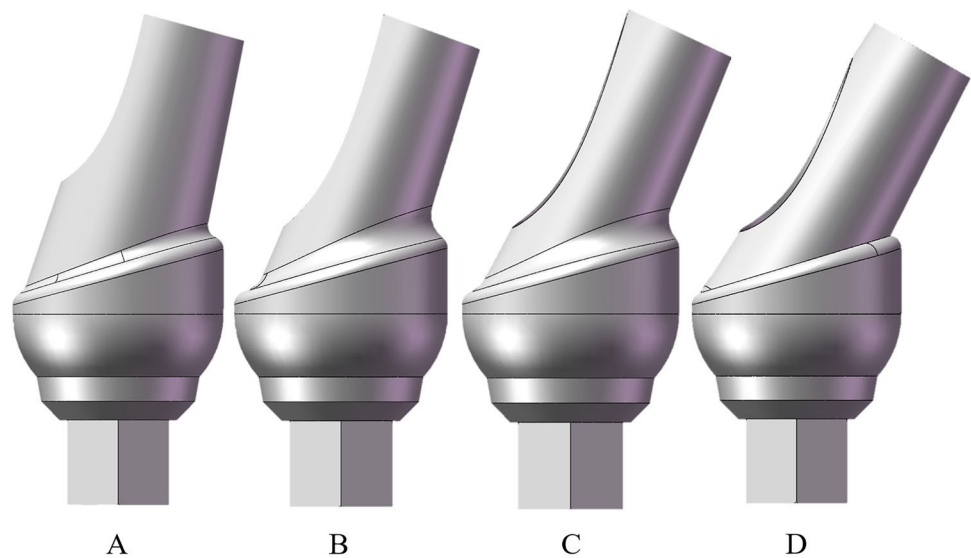


Fig. 2 Angular abutments. **A** 15° angular abutment; **B** 20° angular abutment; **C**, 25° angular abutment; **D**, 30° angular abutment



implant crown as a reference, preserving only the first molar part of the maxillary posterior region. The cut geometry was imported into Hypermesh 2022 (Altair, USA) software and meshed according to each part of the assembly.

The model uses a 10-node tetrahedral cell, which has secondary displacement patterns and is able to simulate irregular geometries better. Mesh refinement using convergence test. For convergence monitoring, the maximum von Mises stress in the mandible was used with a tolerance of 5%, indicating that convergence was considered to be achieved if the change in both cortical and cancellous bone was less than 5%. Adaptive convergence was achieved when the two subsequent mesh refinements had little effect on the results, with a mass cell size of 0.1 mm. The number of cells for all models is 6960000–7155801 and the number of nodes is 1439924–1472137.

2.3 Material properties

The material of the implant, angled abutment, and central screw is Ti6Al4V. Matching implant crowns, made of feldspathic porcelain, were constructed from the angled abutments, implants, and intermediate screws in the modeling software SolidWorks 2021 by means of an assembly of origin combinations. The matching implant crown is built in the modeling software SolidWorks 2021 according to the angled abutment, implant, and central screw, and the material of the implant crown is feldspar porcelain. The material properties of each part of the geometric model are shown in Table 1. All materials were presumed to be linearly elastic, homogenous, and isotropic. The interface between the implant and bone was bonded to simulate ideal osseointegration, the angled abutment was 100% connected to the all-ceramic crown [24, 25].

2.4 Loading and boundary conditions

The models in each group were set up with the sinus cortical bone at the sinus as a fixed support surface, and the contact between the model parts was set up in a bonded mode [22]. Since oral masticatory movement is a constantly changing process, static loading is difficult to realistically simulate the force applied to the model during mandibular movement. Oguzkayabas et al. [27] scholars compared the dynamic and static loading experiments on implants and found that dynamic loading is more likely to result in the destruction of the restorations compared to static loading. Dynamic loading by simulating the posterior masticatory process is closer to the real results. Therefore, in this experiment, dynamic forces were loaded sequentially on the implant crowns simulating the five force states of the masticatory cycle, respectively, with the cortical bone of the maxillary sinus as the support and the fixed binding contact between the parts, and the magnitude of the loaded force was set at 150 N [28]. The force was applied to the implant crowns in the same way as the masticatory cycle, with the cortical bone of the maxillary sinus as the support. The specific loading time, size, site, and direction are shown in Table 2.

2.5 Calculation analysis

Ansys Workbench 2022 R1 (ANSYS, USA) finite element analysis software was used to analyze and calculate the equivalent forces and stresses of each model in each force phase of the simulated oral mastication dynamic cycle for each of the three groups of models under dynamic loading conditions. The stress distribution in the FEA was color-coded to allow the comparison of the biomechanical differences among models.

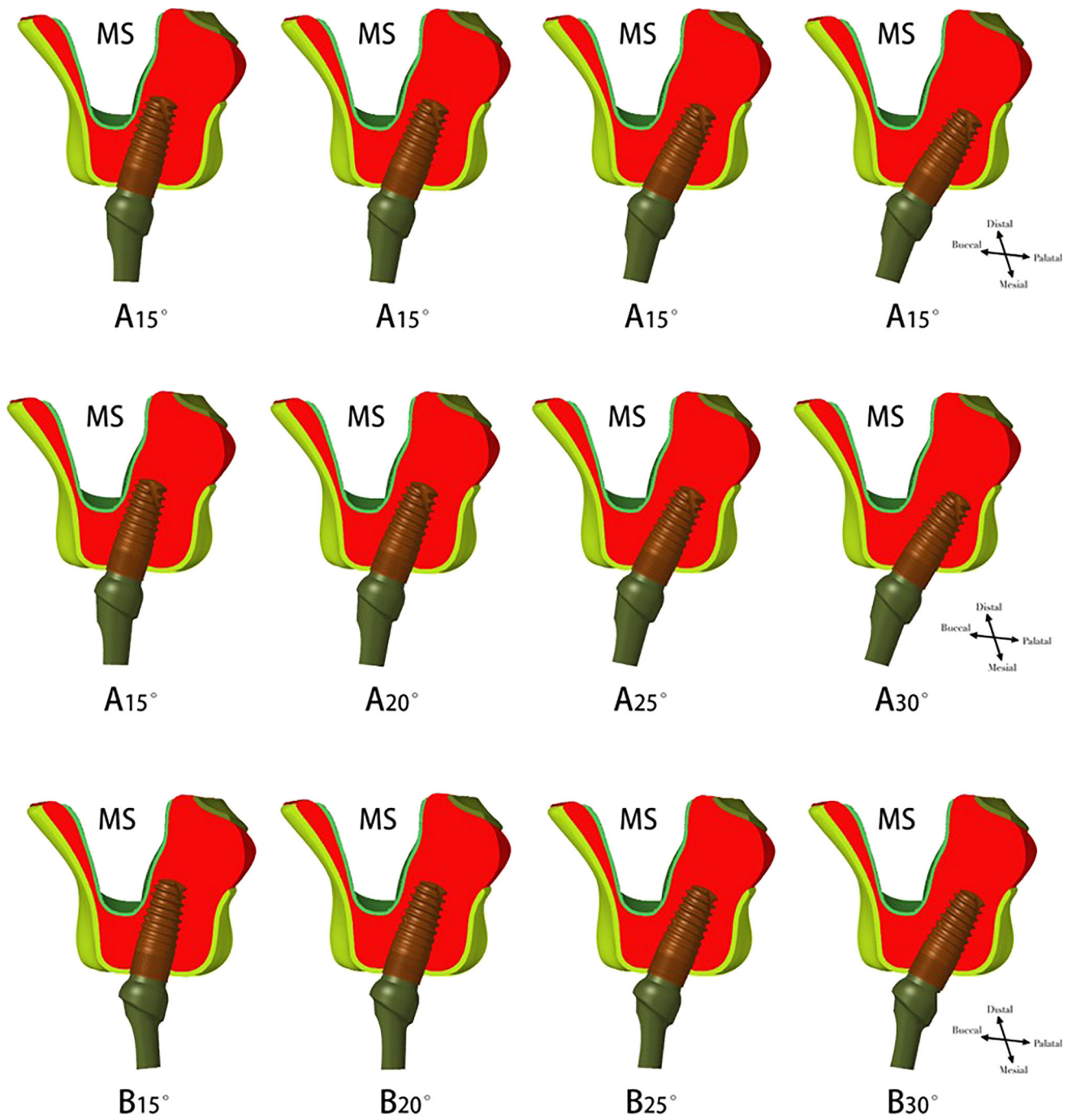


Fig. 3 Tilted implant model using angled abutments. MS, maxillary sinus; I: A_{15° , B_{20° , C_{25° , and D_{30° models are tilted 15°, 20°, 25°, and 30° using angular abutments of 15°, 20°, 25°, and 30°, respectively; II: A_{15° , A_{20° , A_{25° , and A_{30° models are tilted 15°,

20°, 25°, and 30°, respectively, using 15° angular abutments; III: B_{15° , B_{20° , B_{25° , and B_{30° models are tilted 15°, 20°, 25°, and 30° respectively using a 20° angular abutment

Table 1 Material parameters of the model [26]

Material	Young's modulus (GPa)	Poisson ratio
Ti6Al4V	110	0.35
Cortical bone	13.7	0.30
Sinus cortical bone	13.7	0.30
Cancellous bone	1.10	0.30
Feldspar porcelain	68.9	0.28
Maxillary sinus mucosa	0.058	0.45

3 Results

3.1 Stress on the peri-implant bone tissue

ANSYS finite element analysis software can be used to perform the analysis of the magnitude, concentration, and dispersion of the stress–strain distribution of oral dental implants and their surrounding hard and soft tissues. The stresses in the cortical bone tissue were all higher than the surrounding tissues, and this behavior was shown in all the simulations, and the results were consistent with the stress distribution results obtained from the three-dimensional finite element analysis of the implants by Ao M [29], Young-II Kang et al. [30]. The simulation results showed that the buccal region of all models showed stress concentration when the external force was applied in the palatal direction, as shown in Fig. 4

As shown in Table 3, in the models of Groups I, II, and III, the peak cortical bone stresses all appeared in the fourth stage of the dynamic loading cycle and increased roughly with the increase of the tilt angle, which was consistent with the experimental results of Lv Jia et al. [31]. The cortical bone stress and strain peaks were at D_{30° , A_{30° , and B_{25° , respectively, and the stress maxima were 32.065 MPa, 38.344 MPa, and 29.256 MPa, and the strain maxima were 2425 $\mu\epsilon$,

Table 2 Loading amount, position, direction, and time at different stages of a chewing cycle

Loading time	Force(N)	Loading position	Loading direction
0 0.13s	–	–	–
0.13 0.15s	150	Tip of tongue	vertical
0.15 0.26s	150	buccal pointed tongue bevel	The lingual side is inclined to the buccal side and the long axis of the tooth is 45°
0.26 0.30s	150	cheek pointed cheek bevel	Buccal oblique to lingual and long axis of tooth 45°
0.30 0.875s	–	–	–

2912 $\mu\epsilon$, and 2157 $\mu\epsilon$, respectively. The equivalent stress peaks of the cortical bone of the model in group II, which used a 15-degree angle abutment, were significantly higher than that of the other two groups. Among all the models, the peak stress of cortical bone in the A_{30° model was the largest at 38.344 MPa, which did not exceed the maximum tensile and compressive strengths of cortical bone, which were 100 MPa and 173 MPa, respectively [28].

In all three sets of models, the peri-implant bone tissue showed a significant stress concentration in the portion between the implant and the maxillary sinus at a tilt of 15° as shown in Fig. 4. As shown in Table 4, in all three sets of models, the peak cancellous bone stresses appeared in the fourth stage of the dynamic loading cycle, and the cancellous bone stresses and strains roughly tended to decrease with the increase of the angular abutment angle. The equivalent stress and strain peaks of cancellous bone in group I, II, and III models were C_{25° , A_{20° , and B_{15° , respectively, and the stress maxima were 3.768 MPa, 3.861 MPa, and 9.531 MPa, respectively, and the strain maxima were 5809 $\mu\epsilon$, 6133 $\mu\epsilon$, and 4707 $\mu\epsilon$, respectively. The smallest model of the strain peak of the cancellous bone among all the models was B_{30° , and the equivalent effect becomes 3460 $\mu\epsilon$. Among all the models, the B_{15° model had the largest peak equivalent force of 9.531 MPa for cancellous bone. The maximum tensile and compressive strengths of cancellous bone were not exceeded, 61.24–81.11 MPa and 103–150 MPa, respectively [32, 33]

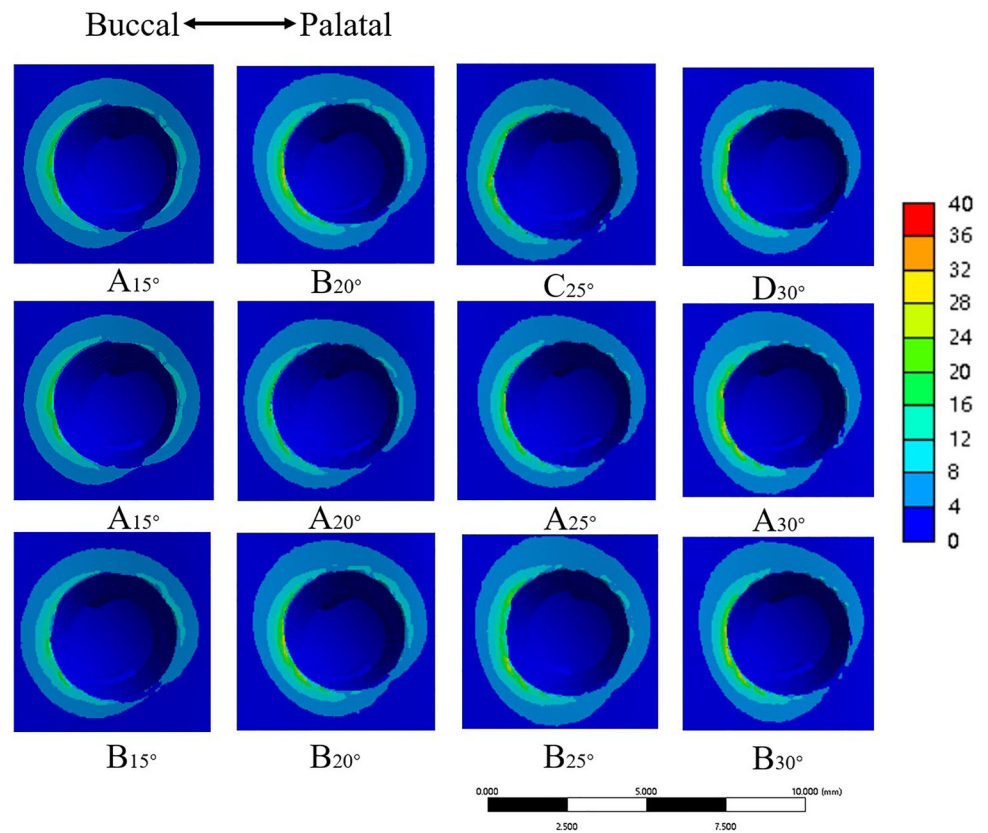
3.2 Location of stress and strain maxima in the bone tissue around the implant

The stresses in the cortical bone of the three models were concentrated at the point of contact between the implant and the cortical bone, and the peak stresses were all located on the buccal side of the implant neck, as shown in Fig. 4, when the lateral palatal tilt angles of 15°, 20°, 25°, and 30° were set according to the set three models. As shown in Fig. 5, the peak strains in all three model groups were concentrated at the contact between the bone interface and the threads at the base of the implant, and all occurred on the side of the peri-implant bone tissue near the maxillary sinus. At a tilt angle of 15°, a stress concentration was observed in the portion between the implant and the maxillary sinus that was distinct from the other tilt angles.

4 Discussion

The analysis of stress in the implant, stress and strain concentrations around the peri-implant bone structures is extremely important for a good clinical prognosis of dental implant rehabilitation since bone loss/resorption and implant stability are directly associated with the biomechanical

Fig. 4 Stress cloud of the bone tissue around the implant at peak stress. Stress peak at 0.30s of dynamic loading



characteristics of the dental restorations and bone. According, the FEA plays an important role in solving engineering problems in many fields of science, and it can be successfully applied in simulations of biomechanical systems. FEA plays an important role in solving engineering problems in many fields of

science, and it can be successfully applied in simulations of biomechanical systems. FEA is a technique for reconstructing and assessing the stress, strain, and deformation of structures, and it is becoming an increasingly useful tool for predicting the effects of stress on implants and their surrounding bone [34, 35]. Many of the objects to be studied and

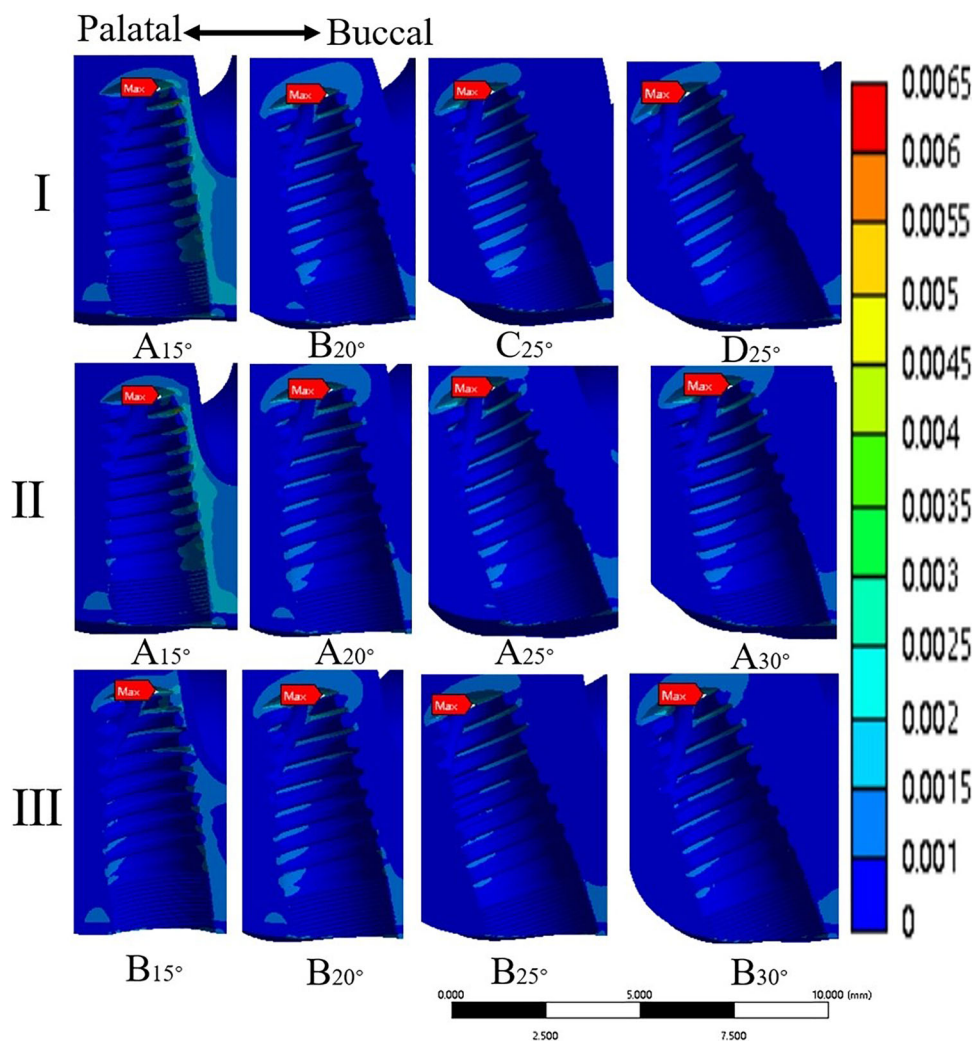
Table 3 Stress and strain peaks of cortical bone at different moments for each group of models

Group	Model	Stress(MPa)			Stain		
		0.15s	0.26s	0.30s	0.15s	0.26s	0.30s
I	A _{15°}	15.851	10.864	26.073	1160	797	1911
	B _{20°}	15.079	9.144	27.813	1102	668	2031
	C _{25°}	18.581	15.450	31.111	1368	1132	2334
	D _{30°}	16.537	14.366	32.065	1217	1069	2425
II	A _{15°}	15.851	10.864	26.073	1160	797	1911
	A _{20°}	17.401	12.483	28.261	1225	983	2089
	A _{25°}	19.474	13.068	34.973	1427	958	2562
	A _{30°}	14.410	16.022	38.344	1095	1216	2912
III	B _{15°}	14.688	8.643	25.035	306	123	968
	B _{20°}	15.079	9.144	27.813	1102	668	2031
	B _{25°}	14.401	12.478	29.256	1065	919	2157
	B _{30°}	15.876	9.905	28.582	1159	723	2092

Table 4 Stress and strain peaks in cancellous bone at different moments for each group of models

Group	Model	Stress(MPa)			Stain		
		0.15s	0.26s	0.30s	0.15s	0.26s	0.30s
I	A _{15°}	2.662	1.898	3.043	4430	3158	4906
	B _{20°}	2.890	1.464	2.907	4665	2409	4669
	C _{25°}	3.264	2.018	3.768	5097	3135	5809
	D _{30°}	2.019	1.157	2.309	3316	1863	3684
II	A _{15°}	2.662	1.898	3.043	4430	3158	4906
	A _{20°}	3.429	1.902	3.861	5445	2978	6133
	A _{25°}	2.618	1.817	3.347	4308	2976	5363
	A _{30°}	2.444	1.677	3.116	3811	2684	4941
III	B _{15°}	7.481	3.644	9.351	3752	1842	4707
	B _{20°}	2.890	1.464	2.907	4665	2409	4669
	B _{25°}	2.824	1.667	3.018	4492	2650	4681
	B _{30°}	2.097	1.138	2.164	3435	1881	3460

Fig. 5 Strain cloud of the peri-implant bone tissue at the peak of the strain. Stress peak at 0.3s dynamic loading



treated are actually continuous. In finite element analysis, the region to be studied is partitioned into small units connected by many nodes. By doing so, the problem is reduced to values with only a finite number of discrete points. Thus, it is possible to transform infinite degrees of freedom into finite degrees of freedom and, since the elements can be divided into different shapes and sizes, it adapts well to complex geometries, material properties, and boundary conditions. Finite element analysis allows the analysis of mechanical properties of materials and very complex geometric regions of biological structures [36].

The current 3D finite element method includes static (unchanging) and dynamic (changing over time) loading methods. The dynamic load refers to the load that changes with time in relation to the amount and direction of the external force; this causes the force to generate elastic vibrations or vary in velocity. Masticatory movement is a complex oral reflex activity. The effect of occlusal forces on the teeth and their supporting tissues varies at different stages of mastication, and the deformation and stress distribution in the

supporting tissues vary with the duration of mastication. Menicucci et al. [37] found that stresses on the implant and its surrounding bone tissue were influenced more by the duration of loading than by the strength. In this study, the mastication period was divided into five phases; the loading forces were equal in each phase, but the loading time, loading direction, and loading position changed dynamically. The dynamic loading pattern resembles oral biomechanics and is more consistent with masticatory movements [38].

In this study, several assumptions were made during the development of the model. The structures in the model are all assumed to be homogeneous and isotropic and linearly elastic. The maxilla is an anisotropic material and lacks relevant mechanical parameters, making it difficult to accurately simulate and calculate during practical modeling. The elastic modulus of maxillary cancellous bone is more complex than that of cortical bone, and it has been suggested [39–41] that finite element analysis using effective isotropic elastic modulus can predict the mechanical characteristics of cancellous bone. Therefore, the present experiments assume each

structure as a continuous, homogeneous, and isotropic linear-elastic material, and the obtained results still maintain a good mechanical similarity to the actual situation. Besides that, all interfaces between materials are assumed to be bonded or osseointegrated [42–44]. The implant-bone interface (100%) was established and does not necessarily mimic the clinical situation [42]. These are inherent limitations of this study.

The magnitude of the occlusal force is affected by a variety of factors, and the occlusal force generated during mastication varies greatly among individuals and dental positions. The occlusal force range for chewing food under daily conditions is from 3 to 30 kg (about 29–294 N), and in this study, 150 N was selected as the loading force for the three force states, which is consistent with the range of occlusal force in normal humans.

In finite element analysis studies evaluating mechanical stresses around implants, usually, von Mises stress is the most commonly used scalar stress metric to assess the yielding/damage behavior of various materials [45]. In this study, the stress cloud stresses in the bone tissue around the implant showed that the stresses in each model were mainly concentrated in the cortical bone around the implant neck, and the stress levels in the cancellous bone were much lower than those in the cortical bone, similar to previous studies [46, 47]. This can be explained by the principle of stress shading: a system consisting of 2 or more components with different moduli of elasticity under load, the component with the higher modulus of elasticity will carry more of the load. When the stress is transmitted from the implant to the bone interface, the cortical bone is subjected to a higher stress because its elastic modulus is significantly higher than that of cancellous bone. This was also confirmed by [48] in their study of angled and straight abutments.

According to [49] occlusal forces affect an oral implant and the surrounding bone. According to bone physiology theories, bones carrying mechanical loads adapt their strength to the load applied on them by a bone modeling/remodeling process. In previous studies, it was generally accepted that peri-implant healing is directly related to bone remodeling. This remodeling is largely driven by mechanical loading [50], exposing bone tissue to a certain mechanical load usually leads to bone formation or bone loss (the latter applies when too high or too low a force is applied in a restricted area). It has been reported [43, 51] that bone tissue is in a state of adaptation when external forces produce 200–1000 $\mu\epsilon$, in a state of moderate overload when greater than 1000 $\mu\epsilon$, and in a state of pathological overload when bone tissue deformation exceeds 3500 $\mu\epsilon$, which leads to bone resorption when the strain on bone tissue is less than 200 $\mu\epsilon$ or greater than 3500 $\mu\epsilon$. In this study, as shown in Table 4, the maximum strain values were greater than 3500 $\mu\epsilon$ for both Group I and Group II models, and greater than 3500 $\mu\epsilon$ for Group III models B_{15° , B_{20° , and B_{25° models, which exceeds this

threshold, suggesting a risk of bone resorption. The strain value of the B_{30° model is 3460 $\mu\epsilon$, which is less than 3500 $\mu\epsilon$, showing a good mechanical level.

In this study, the three sets of modeled von Mises stresses were concentrated in the buccolingual cortical bone, with higher buccal stresses, as reported in previous finite element studies [49, 52]. This suggests that the buccolingual neck of the implant is a stress-concentrated region. However, the intensity and area of the stress-concentrated region varied among the models, suggesting that the implant position, angled abutment, and implant tilt angle have an effect on the stresses in the implant and its surrounding bone tissue. Numerous clinical studies have reported substantial alveolar bone loss around the implant neck in the case of implant denture implant failure. Numerous animal experiments [53] and clinical studies [54] have shown that: in the presence of unfavorable occlusal forces, this can lead to loss of bone tissue around the dental implant, which in turn can lead to implant failure. Unsuitable loading results in excessive stress concentration in the bone of the jaw around the dental implant; when the stress value reaches the tolerance value of the bone of the jaw, it results in the disruption of the balance between osteoblasts and osteoclasts, and a proliferation of osteoclasts; the final result is the resorption of the bone tissue, the loosening of the implant, the dislodgement of the implant, and the failure of implant restorations. From the data of each group of models, the stress–strain of the cortical bone increased with the increase of the tilt angle, and the stress–strain of the cancellous bone showed a generally decreasing trend. The reason for this is that the direction of the force when loading the second stage vertically was the same as the long axis of the tooth, and the force was dispersed to the surrounding cancellous bone through the crown, abutment, implant threads, and the bottom of the implant, which resulted in a more uniform distribution of the stress without a concentration of stress in a certain point, whereas the model was subjected to an increase in the shear force when loading in an oblique direction, which resulted in a significant concentration of the stress.

Abutment fracture is one of the most common mechanical complications of implant restorations [55]. A retrospective clinical study by Hajimiragha H [38] found that the incidence of abutment fracture within four years of implant restoration was 0.5%, which is a serious complication. The maximum abutment stress was concentrated in the neck of the abutment, which is the most likely site of fracture in clinical practice. The abutment stress is 3.9–5.5 times higher than the vertical load when the abutment is subjected to lateral force, indicating that lateral force is an important factor leading to abutment fracture in clinical practice. Therefore, the rational use of angled abutments for tilt implantation is of great significance. The formation of osseointegration between the implant and the surrounding bone tissue is a key factor in the success of the implant [56], while the peri-osseous

mechanical environment plays an important role in osseointegration. The use of angled abutments changes the direction of occlusal force propagation and the distribution of bone tissue stress, which is more likely to cause stress concentration and lead to peri-implant bone resorption [57, 58]. In this study, in terms of angular abutment use, the combined stress–strain data showed that using a 20° angular abutment was more advantageous for tilt angles greater than 15° but not more than 30°. Angled abutments can compensate for the difficulties in repairing the superstructure and improve the aesthetic effect, etc., but for its safe angle range, some scholars suggest that the maximum angle should be controlled at 25° [59–61], or even preferably below 20° [62, 63], which is consistent with the conclusions reached in this study.

In all three models, when the implants were placed using different angled abutments with an inclination angle of 15° toward the palatal side, a significant stress concentration was observed in the area between the implant and the maxillary sinus. This is due to the small distance between the caudal part of the implant and the sinus cortical bone and cancellous bone intersection, where the thickness of the cancellous bone is too small, thus not providing effective support, resulting in high cancellous bone strain and stress at the caudal part of the implant and on the buccal side of the implant.

In this study, the models were considered to be 100% osseointegrated, although that is essentially impossible in the actual clinical process. Therefore, some differences between this study's results and clinical practice are likely. However, the dynamic loading method was used to simulate oral masticatory movement more accurately than other static loading models, and this should be carried over into the clinical realm. Further studies suggest collecting more jaw bone models that meet the inclusion criteria so that more 3D finite element models are available for analysis; longitudinal clinical trials will also provide important data. This study provides a biomechanical rationale for tilted implant surgery in patients with missing maxillary first molars and insufficient bone volume.

5 Conclusions

In this study, the effect of changing the abutment angle and tilted implant angle on the stress distribution of the peri-implant alveolar bone was found to be biomechanically superior to other angled abutments and tilted implant angles, using an angled abutment with a tilted angle of 20° for implants with a tilted angle of 20°, 25°, and 30°, in the case of insufficient bone volume of the maxillary first molar. In future studies, it may be possible to improve implant material and consider bicortical bone fixation to reduce the stress on cancellous bone and thus improve the success rate of implant placement in the long term. Because of the generalizability

of this study, it can provide a theoretical basis for the rational use of angled abutments and tilted implants in clinical implant restorations in various countries.

Author contribution Peng Chen: writing—original draft, conceptualization, software, formal analysis, visualization. Jianguo Zhang: formal analysis, validation, writing—review and editing, funding acquisition. Juan Yao: conceptualization, resources, supervision. Fengling Hu: validation, project administration. Liang Song: methodology. Youcheng Yu: investigation, resources.

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Declarations

Conflict of interest The authors declare no competing interests.

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